**Annular Fuel Rods**

- Internally and externally cooled light water reactor (LWR) fuel rod
- Annular design increases cooled surface area and reduces conduction thickness, improving heat transfer

- VIPAC fuel is created by vibration and mechanical packing of SiO₂ particles (25-500 μm diameter) to replace solid pellets
- 4" long annular VIPAC rods with Zircaloy cladding were manufactured by AECL for irradiation in MIT reactor
- Achieved 82% TD; increased density to 87.5% TD by including 15% U metal powder in some samples

**Silicon Carbide Cladding**

- SIC cladding could replace traditional zirconium-alloy fuel rod cladding
- Cladding has ~15 mm outer diameter and is 3.7 m long
- Duplex design has an inner layer of solid SIC with outer layer of wound SIC fibers

- SIC has favorable physical properties when compared to Zr:
  - Lower neutron absorption
  - No creep deformation
  - Can withstand higher temperatures
  - Chemically inert
  - Higher strength
  - More resistant to radiation damage

**Fuel Rod Simulation**

- FRAPCON steady-state fuel rod code was used to predict the behavior of a full-sized SIC-clad fuel rod in a power reactor
- Examined the performance at high power (30 kW/m) and up to high burnup (100 MWd/kgU, compared to 65 MWd/kgU maximum achieved today)
- Higher temperatures due to lower thermal conductivity, wider gap
- Less cladding stress due to delayed pellet-cladding contact
- Performance can be improved by careful sizing of initial dimensions
- More favorable behavior with annular or VIPAC designs

**Cladding Irradiation**

- SIC cladding samples are being irradiated in the MIT reactor
- Samples are contained in an isolated PWR flow loop:
  - 0.25 kg/s H₂O
  - 300°C, 10 MPa (reactor primary coolant is 50°C, 1 atm)
  - Water chemistry controlled with ppm levels of boron and lithium and 30 ccc/kg H₂
- Testing various surface treatments, composite and monolith constructions, and ceramic bonding agents
- Selected samples may be withdrawn from, and added to, the loop during brief shutdowns
- Planned post-irradiation examination includes strength testing, SEM, spectroscopy, and weight loss measurements

**Post-Irradiation Examination**

- Gamma spectroscopy was performed on both irradiated capsules in a hot box facility at the MIT reactor
- A 1/16" wide, 20" thick lead and steel collimator was used to perform a piecewise axial scan
- Location and relative activity of isotopes confirmed the ORIGEN calculations
- Bump was calculated using both the total Cs¹³⁷ activity and the ratio of Cs¹³⁴ to Cs¹³² count rates
- Fission gas release was calculated using the ratio of Kr⁶⁰ activity in the fuel versus the plenum

**Irradiation of Annular Fuel**

- Two annular VIPAC rods (with 5% enriched UO₂ fuel) were irradiated in the core of the MIT research reactor to 104.5 EFPD at 5 MWₑ
- Rods were sealed in annular aluminum capsules with Pb-Bi eutectic fill and He cover gas to allow for higher temperatures and for isolation from reactor coolant
- Irradiation was also modeled using MCNP/MONTEBURNS and ORIGEN

**Nanofluids**

- Nanofluids are engineered colloids: a base fluid (water, organic liquid) + nanoparticles
- Nanoparticle size: 1-100 nm
- Nanoparticle materials: Al₂O₃, ZrO₂, SiO₂, CuO, Fe₃O₄, Au, Cu, C (diamond, PyC, fullerene etc.)

Previous studies suggest nanofluids allow significant enhancement of:
- Thermal conductivity (+40%)
- Single-phase convective heat transfer (+40%)
- Critical Heat Flux (+100%)

**Nuclear Power Applications**

- Pressurized water reactor (PWR) main coolant
  - Design target is to increase the core power density:
    - +20% in existing PWRs
    - +40% in future PWRs
  - Minimize reactivity penalty and activation
  - Constraints on performance:
    - For uprates, retain design of main reactor components
    - No fuel melting at 112% overpower
    - MDNBR > 1.3 at 112% overpower
- Safety systems for LWRs
  - Limiting condition is fuel temperature during re-flooding of the core following large-break loss-of-cooling accident
  - Need to understand behavior of coolant both before and after reaching the critical heat flux
  - In-vessel retention
    - Ensuring removal of decay heat from the core vessel for high-power density LWRs
- Research Programs
  - Thermal conductivity
    - Tested 15 nanoparticles in H₂O and ethylene glycol using transient hot wire technique
    - Negligible effect up to 18 v/o nanoparticles
  - Convective heat transfer and pressure drop
    - Testing of alumina and zirconia nanoparticles in a heated flow loop
    - No heat transfer or pressure drop enhancement for sub-cooled flow
  - Critical heat flux
    - Significant pool and flow CHF enhancement with low amounts of ZrO₂, Al₂O₃, C, SiO₂
    - Nanoparticles deposit on boiling surface and wettability of the surface is increased
    - This behavior and experimental observation conforms to the Hot/Dry Spot Theory (Theofanis and Dimh, 2006)